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A USN Strategy for Mechanical and Propulsion Systems Diagnostics and Prognostics, Life Usage Monitoring and Damage Tolerance: Applications to Aging Aircraft Problems

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ABSTRACT

A US Navy strategy has been generated to develop and demonstrate diagnostics, prognostics, health management and life management for propulsion and mechanical systems. How this overall strategy has evolved and the current status will be presented. The SH-60 platform was selected for the first proof-of-concept effort to develop, demonstrate, and integrate available and advanced mechanical diagnostic technologies for propulsion and power drive system monitoring. Included in these technologies were various rule based and model-based analysis techniques that were applied to demonstrate and validate various levels of diagnostic and prognostic capabilities. These will be discussed and updated. Using past "seeded fault" tests as case examples, various diagnostic methods were used to identify the faults, and various means of applying prognostics, health management and life management are discussed. Other more recent examples of "seeded faults" and related tests will also be discussed as case studies, demonstrating various degrees of diagnostic, prognostic, health management and life management capabilities. Relative rating of the performance of some of the different analysis techniques evaluated will also be discussed. As used in this paper, prognostics is the capability to provide early detection of the precursor and/or incipient fault condition to a component or subelement failure condition; and to have the technology and means to manage and predict the progression of this fault condition to component failure. The benefit of this prognostic approach is increased safety and decreased maintainability costs over the aircraft life cycle, enabling better management of both existing and potential aircraft system faults. This prognostic philosophy will be further embellished, using examples from past and more recent "seeded fault" databases; to define accomplishments and to discuss additional needed demonstration requirements. Multi-variate analysis, reasoners, and information fusion requirements and approaches will also be discussed. Finally, very recent accomplishments, status and future planned efforts for the USN Helicopter Transmission Test Facility (HTTF) and other related test resources will be presented.

BACKGROUND

The U. S. Navy and U. S. Marine Corps have long had a requirement to improve several aspects of their rotary wing operations in order to improve readiness through more effective maintenance, eliminate losses of aircraft and personnel, and dramatically reduce maintenance related costs. The requirements to extend the service life of aircraft and the limitations on manpower have increased the urgency to effect these types of improvements. A majority of the Class A mishaps (loss of aircraft and/or personnel) in Navy helicopters are caused by engine and drive train failures. The need to accurately identify and diagnose developing faults in mechanical systems is central to the

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ability to reduce mechanically induced failures and excessive maintenance.

The U.S. Navy would clearly benefit from a reliable state-of-the-art diagnostic capability on-board rotary wing aircraft. An advanced prognostic capability would provide even further benefits. Based upon the Mission Need Statement (Ref. 1), such a system is expected to enhance operational safety and significantly reduce life cycle cost through it's ability to predict impending failure of both structural and dynamic drive system components and consequently direct on-condition maintenance actions and/or alert the pilot to conditions affecting flight safety.

The evolution of automated diagnostic systems for helicopter mechanical systems has been greatly advanced by the Navy in a program of systematic testing of drive train components having known anomalies (seeded faults) while simultaneously executing a suite of diagnostic techniques to identify and classify the mechanical anomalies. This program, called the Helicopter Integrated Diagnostic System (HIDS) was carried out using both an iron bird test stand and SH-60B/F flight vehicles.

While diagnostic capabilities to detect a specific component failure event are relatively straight forward; prognostic capabilities are less well developed and can have a much larger payoff. Any system considered for fleet-wide implementation should have both capabilities. Any program to demonstrate and validate diagnostic capabilities must also address some degree of prognostics. This program attempts to do both.

There is currently considerable activity underway to develop integrated health and usage monitoring systems particularly for helicopter subsystems (transmissions, rotor head, engines, tail drive systems, etc.). Several tests have been run in the Navy's spin pit facility and Helicopter Transmission Test Facility (HTTF) at Patuxent River Naval Air Station, and these tests will be discussed in this paper along with their applicability to aging aircraft. Also, a discussion of future planned events will be presented in this paper, along with the role they play in mitigating problems traditionally experienced in an aging

OVERVIEW OF HIDS

In 1993, the NAWCAD awarded a competitive contract on the Broad Agency Announcement to Technology Integration Inc. (Now Goodrich Corporation) for two functionally equivalent integrated diagnostic systems. One system was configured for rack mounting in the HTTF and the other is flyable ruggedized commercial grade hardware. The design uses an industry-standard open architecture to facilitate modularity and insertion of new hardware and software. The system is comprised of two main avionics units, the commercial off-the-shelf KT-1 aircraft parameter-usage monitor and the KT-3 vibration acquisition, analysis and rotor track and balance subsystem. System architecture and data flow is shown in Figure 1. Though not a production type unit, the vibration acquisition system is essential to acquire the raw data necessary to substantiate the diagnostics technology and obtain enough knowledge to write the minimum acceptable production specification.

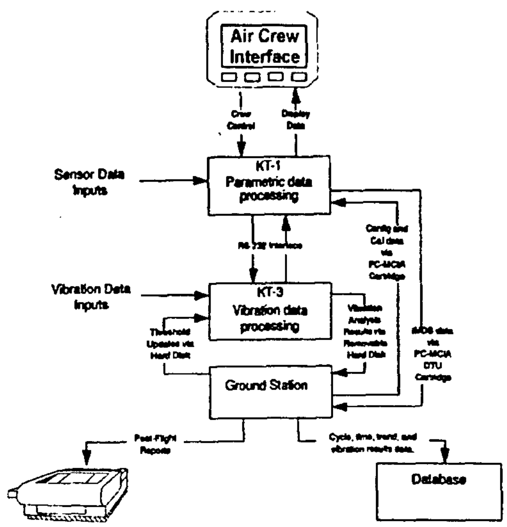

Fig. 1. Diagnostic System Architecture.

Engine Performance: The HIDS Cockpit Display Unit (CDU) depicted in Figure 2 interfaces with the pilot to execute and display results of automated NATOPS T700 engine health checks and the engine Power Performance Index (PPI). The PPI is a fourth order best fit curve representing an engine degraded 7.5% from the specification line, and can provide a warning to the pilot when an engine has degraded due to salt ingestion, sand erosion or other foreign object damage (FOD).

Vibration Based Mechanical Diagnostics: The focal point of this program was to explore a wide variety of diagnostic methods based upon vibration inputs, in a manner that would lead to a

rational selection of reliable "production" techniques with a high confidence in accurate detection with low false alarm rates. Vibration data recorded at both Trenton, NJ and Patuxent River, MD used the same acquisition system, sensors, mounting and accelerometer locations. The data sets are digital time series records, recorded simultaneously for up to 32 channels (accelerometers and tachometers), at 100,000 samples per second, 0-50Khz bandwidth, for 30 seconds. This proof-of-concept system records five sets of raw data per flight for post flight data analysis in the ground station. Drive system accelerometer locations are shown in Figure 3 for the input and main modules and Figure 4 for the tail section. The mechanical diagnostic system algorithms provided by TII/BFG under investigation are "classical", model-based diagnostics. That is, the model is composed of the Sikorsky proprietary gear and bearing tables for the SH-60B drive system. No fault or anomaly detection training is required. The system provides three significant contributions to the development and verification of diagnostics for helicopters:

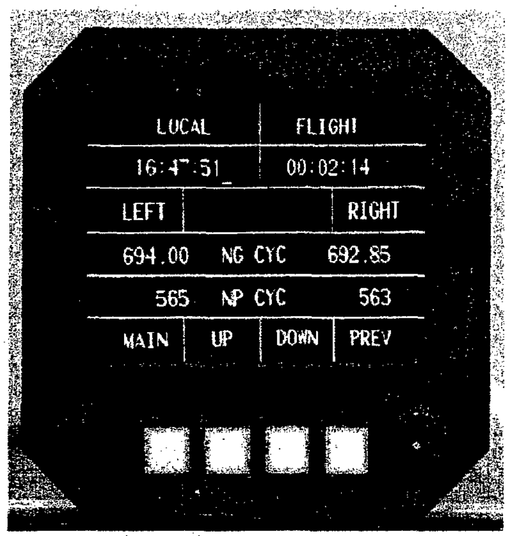

Fig. 2. Central Display Unit.

1. The system acquires data from all channels simultaneously. This makes it possible to use multiple channels to analyze a single component; an essential element of false alarm reduction. Today, the HIDS system is the only flying data acquisition system that has demonstrated the ability to record the raw and processed data set for an entire aircraft propulsion and power drive system. The HIDS system saves raw time series data, for all channels including tachometers for post flight evaluation and future algorithm development. This minimizes the possibility that a malfunction in the preprocessing could contaminate the database.

2. The system has the capability to automatically adjust to provide good signal to noise ratios for all channels. The system starts each acquisition with a one second sample, and internally sets the gains based upon the measured signal amplitude to maximize dynamic range. The gain for each channel is recorded with the raw data for future analysis.

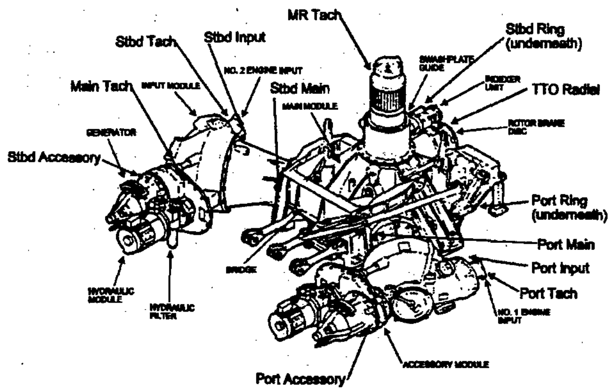

Fig. 3. Accelerometer Locations on Input and Main Modules.

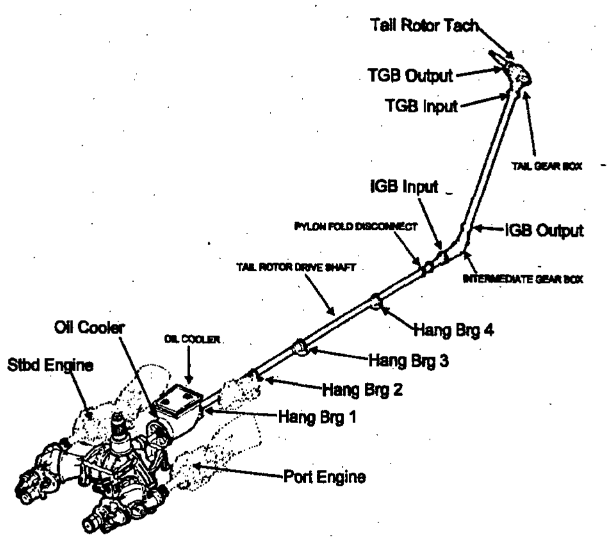

Fig. 4. Accelerometer Locations on the Tail Drive System.

3. Capability for on-board processing. All gears, bearings and shafts are analyzed and the diagnostic results are written to the aircraft parameter data file according to flight regime. The raw data files can be held in RAM until the analysis is complete, then discarded if no anomalies are identified by the limit check. If a parameter is deemed to be in "maintenance" or "alarm" status by exceeding preset limits, the component of concern would have all of the accelerometers that are used for its analysis plus the aircraft tachometer saved as raw digital time series data for post flight investigation. When data is taken in response to a pilot-activated switch, raw data is written to disk with all of the analysis results. The HIDS program is in the process of determining alarm limits and algorithm sensitivities to achieve this goal and level of integration.

Vibration Based Prognostics: Though it is often difficult to separate diagnostic and prognostic performance in a seeded fault program such as this, one of the by-products of this testing was the demonstration of the potential and performance of prognostics.

As a working definition for this paper: prognostics is the capability to provide early detection of the precursor and/or incipient fault condition to a component or sub-element failure condition; and to have the technology and means to manage and predict the progression of this fault condition to component failure. The early detected, "incipient" fault condition, is monitored, "tracked", and safely managed from a "small" fault as it progresses to a "larger" fault, until it warrants some maintenance action and/or replacement. Through this early detection and monitoring management of incipient fault progression, the health of the component is known at any point in time and the future failure event can be safely predicted in time to prevent it.

Applying many of the same algorithms and techniques used for vibration based mechanical diagnostics, a significant degree of component failure prediction and prognostics was demonstrated during these tests. Often the extrapolation of vibration frequency data, statistical parameters and/or diagnostic indicator trends is the technique used to enable failure prediction. It is of course key to have sensors, algorithms, and diagnostics indicators (or indices) that are sensitive and accurate enough to "see" the precursor or incipient "small" component fault. It is equally important to have a reliable experience database with examples of similar types of "faults" so that the failure progression rate is understood. Using this experience database knowledge and the understanding of various types of failure progressions will enable the intelligent settings of alarm thresholds. It is envisioned that in most cases, the alarm thresholds for safety-of-flight (cockpit warning) will be significantly higher than for maintenance. Establishing these alarm thresholds is a very necessary step in implementing future failure event prediction and enabling prognostics. Without the benefit of an extensive experience database of actual component failures with fault progression data and/or a comprehensive "seeded fault" trials as the SH-60 HIDS program, establishing these alarm thresholds is virtually impossible.

Rotor Track and Balance: The ROTABS system promises to negate the need for on-board trackers and utilizes higher order mathematics and a significantly larger data set to resolve the adjustments required to keep the rotor system in track and balance.

A continuous monitoring of the in-flight rotor track and balance condition will alert the maintainers of out-of-limit conditions that, among other things, will result in high vibration stress conditions. By keeping the rotor system in a "better" track and balance condition, overall vibration levels on all aircraft structural components and subsystems will be reduced. This could significantly increase the life of many of these aircraft structural components and subsystems. In particular, avionics systems could see a large improvement in life. This capability alone would positively impact several damage tolerance issues on aging aircraft.

Groundstation: The HIDS groundstation houses maintenance, pilot, and engineering windows to support complete health and usage functionality. Tools are provided for parts and maintenance tracking, rotor track and balance, mechanical diagnostics, flight parametric data and flight regime replay, pilot flight logs, and projected component retirement times. During a flight data download, the groundstation calculates flight regimes from downloaded parametric data, and updates life usage on pre-selected serialized components in a database upon aircraft data download. Functions to trigger usage-based maintenance and component replacement are designed into the system. Historical data replay provides regime, event and exceedance information along with all aircraft parameters for the entire flight. Pilot control

inputs are displayed along with all aircraft parameters for the entire flight. Pilot inputs are recorded along with other parameters which is essential for understanding events during a flight. The ground station has been shown to reduce the paperwork associated with daily operations and to direct maintenance personnel to the faulty component identified by diagnostics.

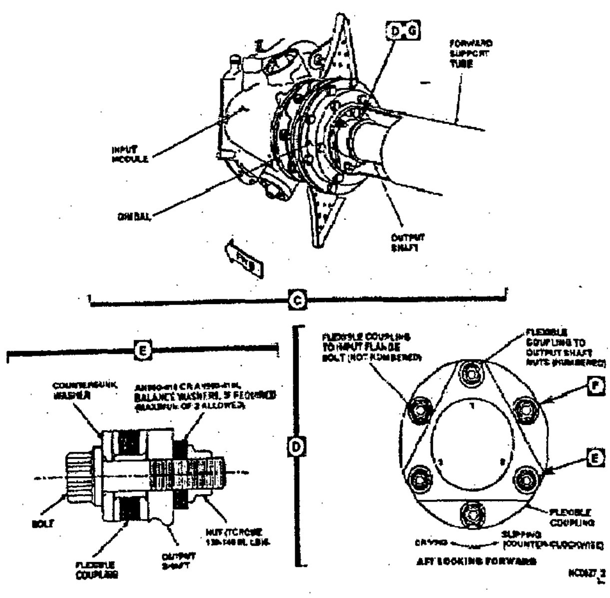

Fig. 5. High Speed Shaft Interface.

DETECTED FAULTS

To obtain this vision of vibration based diagnostics and prognostics, several seeded fault tests have been run to correlate vibration signatures with certain failure conditions. Below is a description and brief discussion of these tests and results.

The HIDS system has demonstrated the ability to identify localized faults on a number of H-60 drive system components. The engine high speed shaft/input module interface (see Figure 5) has been a problem area, where the difficult to inspect Thomas Coupling disc pack has suffered several failures. Other aircraft have suffered similar catastrophic failures. Figure 6 shows the engine high speed shaft (with cracked Thomas Couplings) that was removed from the fleet and tested at Trenton. The HIDS system detected the fault and isolated it to the starboard side. This provides a rationale for providing a cockpit alert for critical, rapidly degrading components.

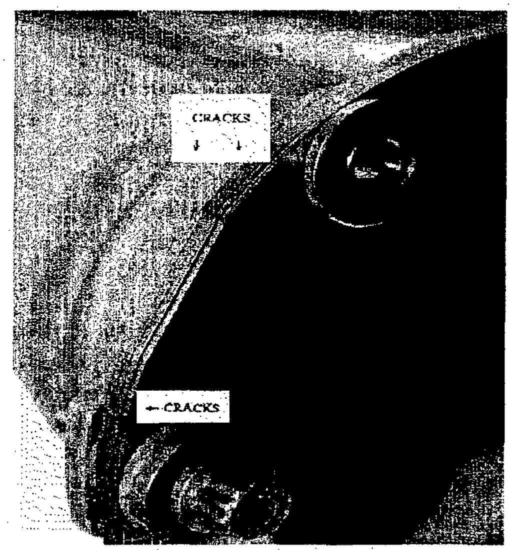

Fig. 6. Cracked Thomas Coupling.

One particular test article was a Coast Guard HH-60J main transmission input module that emanates high vibrations at half of the gear mesh frequency. The Navy has encountered a few incidents of half-mesh input modules, where every other tooth of a semi-hunting mesh is highly loaded. Since both the pinion and gear have even numbers of teeth, wear occurs at a much faster rate. Moreover, aircraft with these half-mesh input modules have a history of rejecting engines because of power turbine shaft wear and resultant cockpit torque indication errors. The Coast Guard rejected one engine on the subject aircraft because of the torque indication problem. The cause of half-mesh anomaly is believed to be gear profile errors introduced in the machining process.

The objectives of the test were to exercise the input module in a highly controlled and instrumented environment to

- develop a reliable method for the Coast Guard to identify half mesh modules using their field vibration equipment,
- determine if Navy tests could be conducted at lower torque than the current 75% requirement, making the test compatible with shipboard operations,
- test a novel fix, indexing the pinion by one tooth thereby changing mating teeth in mesh, and
- return the asset to service if within acceptable vibration limits.

All of the objectives of the test were successfully accomplished, with the exception

that the material condition of the test article precluded a return to service. Prior to initial test run, inspection of the mating gears via the input module inspection port revealed wear patterns and spalling, confirming high loading of every other tooth in the gear mesh (see figure 7). The degree of spalling was unexpected, and required the asset to be overhauled. However, the pinion was still indexed to determine whether vibrations at the half-mesh frequency could be brought to within acceptable limits. As exhibited in figure 8, the vibration was reduced well below the Navy limit of 0.15 IPS, and would have allowed the asset to be returned to service. Reliable limits were developed for Coast Guard field vibration equipment by comparing measurements from several vibration monitoring systems. The chart also shows that a low 40% torque, such as required for single-engine flat-pitch operation, provides similar detection capability as for higher torques. With the real-time monitoring capabilities of the Integrated Mechanical diagnostic System Health and Usage Monitoring System (IMD HUMS) about to enter the fleet, detection of aircraft system faults such as this half-mesh anomaly are automated and performed every flight, lowering operational costs and increasing safety.

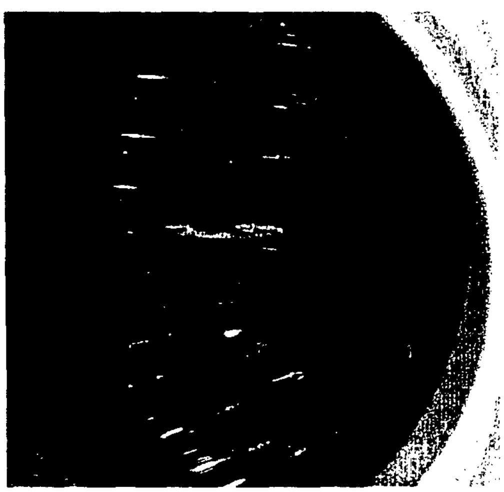

Fig. 7. Half Mesh on Coast Guard HH-60J.

A critical part of the HIDS program is to demonstrate the detection of catastrophic gear faults. The most serious of which are root bending fatigue failures. Depending upon gear design, this type of crack can either propagate through the gear tooth causing tooth loss, or through the web causing catastrophic gear failure and possible loss of aircraft.

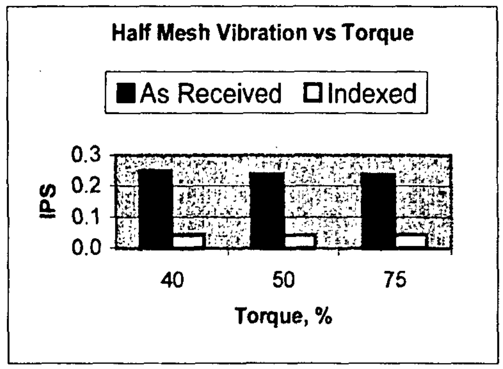

Figure 8: Results from Half Mesh Test

A means used in the helicopter community to promulgate this type of investigation (seeding a fault) is to weaken a gear tooth by implanting an Electronic Discharge Machine (EDM) notch in the gear tooth root. This action creates a localized stress concentration at the tooth root in an effort to initiate a crack. The HIDS team had previously attempted this test on other gear teeth, but with no success. Discussions with the transmission design departments at Agusta Helicopters and Boeing Helicopters helped to determine optimum notch placement. Figure 9 is a cutaway of the SH-60 intermediate gearbox. Two EDM notches (.25" Length x 006" Width x .040" Depth) were implanted along the length of the intermediate gearbox (IGB) gear tooth root by PH Tool of New Britain, PA. The location of the notches is critical as they were implanted where the gear tooth root bending stress is greatest.

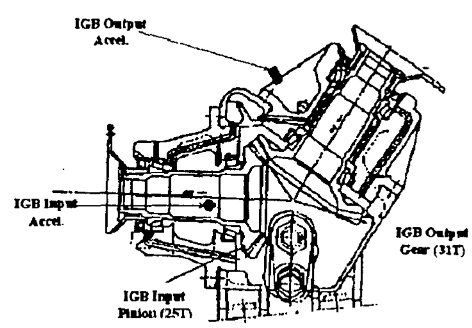

Fig. 9. SH-60 Intermediate Gearbox Cutaway.

The test was run at 100% tail power for a total of 2 million cycles, when testing was terminated prior to gearbox failure when a gross change in the raw FFT spectra was observed on

the HP36650 Spectrum Analyzer. Subsequent to test termination the gearbox was disassembled and inspected. The input pinion's faulted tooth exhibited a crack initiating from the tooth root and extending through the gear web and stopping at a bearing support diameter. Figure 10 exhibits the subject pinion at the end of the test. There is a void at the toe end of the notched tooth where a large section of the tooth broke off, and a large web crack extending to the bearing support diameter. No indication from the gearbox chip indicator was observed.

Fig. 10. Cracked Intermediate Gerabox Pinion.

A review of the diagnostic results shows the model-based algorithms successfully detect the presence of the gear tooth fault. After indicating a healthy gear for roughly 267 minutes (most acquisitions were 15 minutes apart), the indicator levels raised steadily for the next 139 minutes, thereafter exhibiting sharp changes in level until test termination at 548 minutes (Ref. 2 discusses indicator results of another pinion tooth fault). Test results illustrated an EDM notched tooth behaves much like adjacent teeth until the part exhibits fatigue and a crack develops. The crack effectively weakens the tooth in bending, causing the faulted tooth to share load unequally with adjacent teeth. Depending upon the crack path, other dynamic anomalies are manifested. Also, synchronous averaging techniques employed in model-based diagnostics can "filter out" non-synchronous vibration providing a health determination of a specific component.

A root bending fatigue propagation test was repeated on a main transmission input pinion. This test promised to be a more challenging effort for several reasons. First, the main transmission module is a larger and more complex system than the intermediate gearbox. The background noise is greater and the fault is located deep inside a larger housing. The gear form was also different. The intermediate gearbox pinion has a large web, where the main module pinion teeth are closer to the shaft centerline and therefore has a great deal of support at the tooth root. These observances made, the HIDS team determined to investigate the crack propagation properties of the more robust gear form.

Two EDM notches were implanted in the root of one geartooth and run for 12 million cycles at 110% power, removed and inspected, and then tested for another 10 million cycles. After 12 million cycles, small cracks less than 2mm in length emanating from the notch corners were present. Figure 11 exhibits the pinion after another 10 million cycles. A large part of the faulted tooth has broken off, and a crack propagated the length of the part forward (toe end), and aft (heel end) to the bearing support. No indication from the gearbox chip indicator was observed.

Fig. 11. Main Transmission Input Pinion Crack.

These tests demonstrated (1) the HIDS diagnostic algorithms successful early detection of root bending fatigue failures, (2) chip detectors are unreliable for the detection of classic gear failures caused by root bending fatigue, (3) H-60 drive system components are particularly robust, and (4) root bending fatigue cracks on gear tooth forms such as the main

module pinion can propagate through the web (vice only the tooth) to a catastrophic condition.

The HIDS system also attempted to quantify the level of signal for a known defect size to develop operational limits and trending for the SH-60 drive system. As discussed above, the IGB root bending fatigue failure provided excellent results in component fault detection and condition assessment. Actual "Component Condition" indicator, and two gear health indicators which determine the component condition have been identified in the analysis. Early warning of a local gear tooth anomaly is provided by Residual Kurtosis, and Residual Peak to Peak continuously elevates as the gear tooth crack propagates to a severe condition. These indicators could therefore be integrated into the diagnostics package as early warning and impending failure indicators respectively.

Diagnostic system sensitivity to defects and faults in tail drive shafts and bearings was also evaluated. Hanger bearing assemblies are used to support the helicopter tail drive shaft. The main components of the assembly consist of a grease-packed sealed ball bearing that is pressed into a viscous damper bladder and supported by a housing that mounts to an airframe interface. The bearing is expected to be lightly loaded since it doesn't support any significant radial or axial loads, though those imposed from imbalance and misalignment occur in-service. Figure 12 shows the hanger bearing assembly and associated accelerometer installed at the number 2 location in the tail drive system. Since the viscous damper is in the vibration transmission path, there was concern it would inhibit the transmission of high frequency tones from the bearing to the vibration sensor.

A fleet removed hanger bearing with a very light click was installed in the HTTF. There was considerable opinion that the click was due to dirt in the bearing. 12.7 drive system operating hours were accumulated and 129 data points were acquired. A fault would clearly exhibit itself by strong tones at frequencies specific to the inner race defect frequency and also at shaft speed. By comparison, fault-free hanger bearings would not generate bearing defect frequencies. Observing the spectral frequency the former was observed, further lending confidence to the algorithms.

Post test inspection of the bearing revealed that the inner ring was fractured as shown in Figure 13. Also, the bearing was found to have about 1.5 grams of grease remaining, which is within the range normally found in bearings operating to their 3000 hour overhaul life. Hanger bearings with inner race fractures have been known to eventually purge all the grease through the fracture leading to overheating, seizure, and loss-of-aircraft.

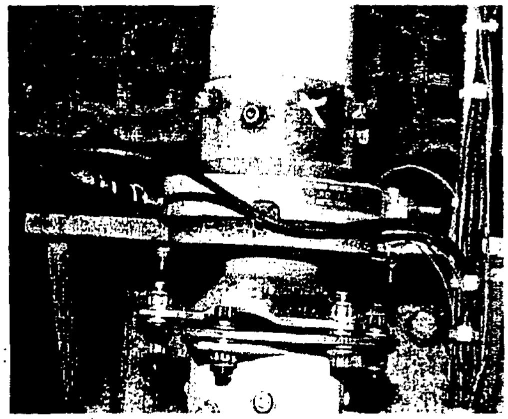

Fig. 12. Hanger Bearing Assembly.

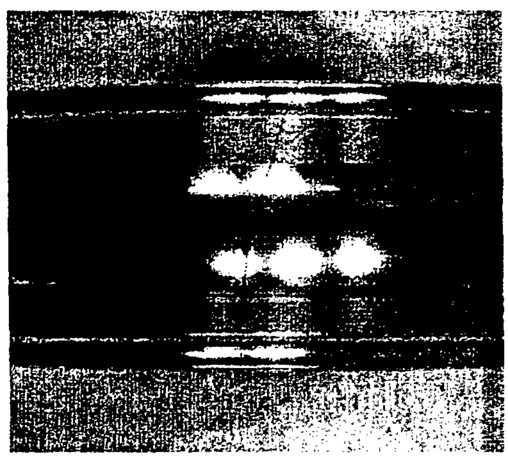

Fig. 13. Post-Test Condition of Hanger Bearing.

The diagnostic system sensitivity to bearing defects in gearboxes was also evaluated. The spalled integral raceway bearing (P/N SB 2205) is the most common dynamic component cause for gearbox removal in the H-60 community. This fault is particularly challenging as it is located deep inside the main transmission, suggesting it would be difficult to detect. Figure 14 illustrates the SH-60 main transmission system and respective vibration accelerometer locations. The Figure 15 fleet rejected component was installed in the HTTF starboard location. The starboard main condition indicator toggles into the alarm position when the fault is

implanted and reverts back to the okay position when the fault is removed. The port main indicator is also sensitive to this fault because the sensor is located on the same structural housing member, and is rotated about 90 degrees around the housing from the starboard main sensor. The port indicator serves as a confirmation of the starboard condition.

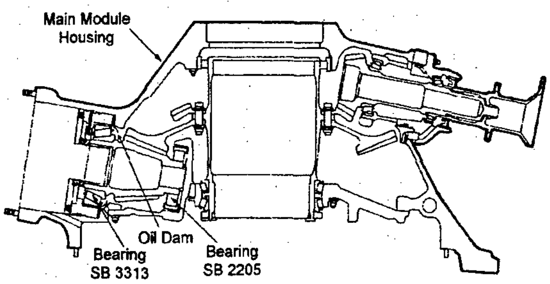

Fig. 14. Locations of SB-2205 and SB-3313 Bearings in the Main Module.

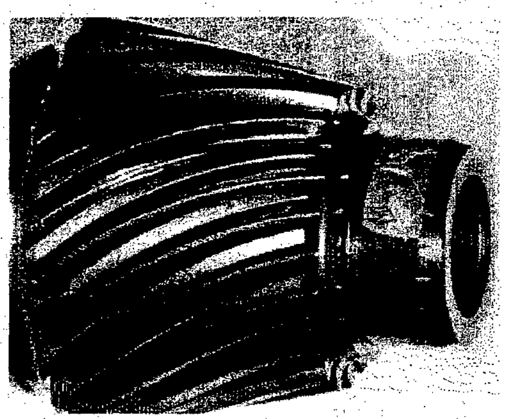

Fig. 15. Main Module Input Pinion with Spalled Integral Raceway Bearing SB 2205.

Prognostics could effectively be applied to the failure of this component. The SB2205 fault progresses in a repeatable manner from a small, localized spall into a larger one that will eventually encompass a good portion of the inner race diameter. At this point, the chip detector will provide an indication of a failure somewhere in the gearbox with no indication of fault location or severity. On the other hand, the model-based bearing indicators identify the presence of the fault early in this process. By carefully tracking the progression of this fault by utilizing the algorithmic indicators, maintenance and mission planning can be conducted in an effective manner, and unscheduled downtime can be effectively reduced.

Evaluation of variability of data across flight regimes (including torque and weight variations) was also conducted. There is considerable difference in the vibration signal between forward flight and hover. This introduced considerable scatter in the algorithm indicators. It was determined a large main rotor 4/rev component (rotor wash) is interacting with the tail pylon in forward flight, which is causing this data instability. This and other flight regime nuances are being investigated.

Evaluation of sensor placement sensitivity for the various defects was performed. The objective is to minimize the total number of sensors required to identify faults large enough to require maintenance action and to increase robustness by verifying use of secondary sensors. The test of bearing SB 2205 provided an interesting study for sensor placement. At the time of test, the stbd main was the primary sensor for the stbd SB-2205 bearing, and the stbd input sensor was the secondary. Test results however showed otherwise. In fact, the enveloped kurtosis of the stbd input sensor does not respond to the fault, whereas the port main sensor does. Based on results from this test, the port main sensor was then mapped as the secondary sensor for the stbd SB 2205 bearing.

This program also undertook an evaluation of the potential for detecting misalignment, bad pattern and improper shimming during assembly that may be the cause of premature damage in mechanical systems. Misalignment and imbalance testing have been performed on a number of drive system components. Specifically, the engine high speed shaft/input module assembly has been investigated under these conditions and findings were documented. Other similar tests (some naturally occurring) were recorded. Gearbox gear pattern shim surveys were also performed. Test results are pending data review.

A seeded fault data library that can be used to evaluate systems in the future without repeating the test program was developed. The HIDS program has provided a wealth of knowledge and understanding of the implementation of mechanical diagnostics. Though not immediately quantifiable, the HIDS testing has identified many optimized test methods and fleet implementation issues. Though not eliminating the need of seeded fault testing for other drive systems, the scope of work can be more precise and reduced. For the IMD HUMS initiative, the

HIDS data is being distributed to various institutions to develop and evaluate transmission planetary system gear and bearing algorithms.

As many currently available propulsion and power drive system diagnostic technologies as possible were evaluated in HTTF, and their relative measures of effectiveness were assessed. Engineering evaluation testing of Stress Wave Analysis, Electrostatic Engine Exhaust Monitoring, Inductive Oil Debris Monitoring, Quantitative Oil Debris Monitoring, Optical Oil Debris Monitoring, Laser Interferometer, and Acoustic Emission have been done in parallel with HIDS testing evaluation at Trenton. Two of these efforts are US Army SBIR efforts. As a means to evaluate the IDM and QDM MKII oil debris monitoring systems simultaneously, a modified main transmission lubrication scavenge apparatus was provided by Vickers Tedeco (See Figure 16). The system attaches to the main transmission module at the normal chip detector location and a positive displacement pump adds sufficient head to pump the oil through an external plumbing arrangement. Sump oil enters the pump, IDM, QDM MKII, and finally the production main module chip detector and returns to the transmission. A fine mesh screen is included to capture particles that are not captured by the QDM MKII and main module magnetic detectors. The Figure 15 main transmission input pinion with a spalled integral bearing raceway was used as a tool to generate debris for the evaluation. This test found the fault generated particles much smaller (5-20 microns) than what a typical bearing fault (>100 microns) is known to produce. This evaluation provided sensitivity and performance information.

The HIDS program also undertook a comparison of the data collected on-board the aircraft with the test cell data to validate the pertinence of test cell proven algorithms for use on-board an aircraft. As part of the HIDS program, drive system vibration data was acquired on 22 and 23 May and 30 August 1995 from SH-60 BUNO 164176 at NAWCADPAX. Data was also collected on two other SH-60 aircraft using the same data acquisition system. The data was acquired primarily to support a next generation diagnostic effort based on neural network technology and designated the Air Vehicle Diagnostic System (AVDS) program. The intent was to acquire raw vibration data on fault-free aircraft to use as a means for baselining the neural network process. For aircraft BUNO 164176 a total of 46 separate acquisitions were taken at several different flight conditions including ground turns, hover in-ground effect, hover out-of-ground effect, straight and level and descent. Torque ranged from 28-100%. Approximately one month after the May data had been acquired from BUNO 164176, HIDS project personnel were informed that the aircraft had set off the main transmission chip detector light. The chip detector events prompted an analysis of vibration data collected from BUNO 164176 using HIDS diagnostic algorithms. The same analysis was also conducted on one of the other aircraft, namely BUNO 162326, to provide a baseline for comparison to aircraft BUNO 164176. The fault exhibits itself by the strong tones at frequencies specific to the main bevel pinion tapered roller bearing (SB 3313) both in the test cell and the aircraft.

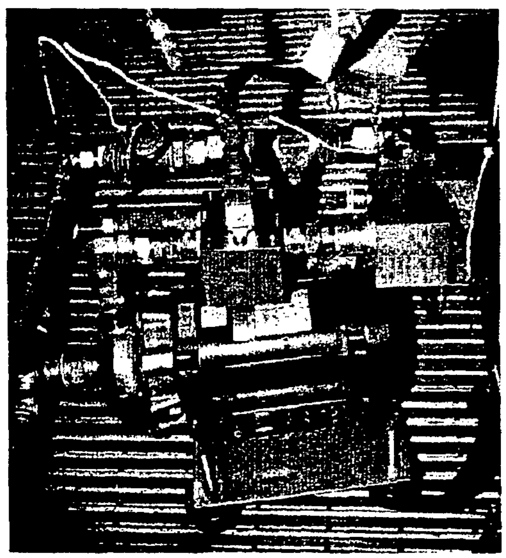

Fig. 16. Test Rig for Oil Monitoring Evaluation.

The analysis clearly indicated a fault in the rolling elements of the starboard main bevel input pinion tapered roller bearing, P/N SB 3313 (see Figure 12 schematic for location) and represented a safety-of-flight concern. Further confirmation of fault location was provided by chip elemental analysis, conducted by Sikorsky Aircraft, which determined that the chips were CBS 600 steel indicating that this bearing was one of several possible sources of the chips. Based on the analysis, the HIDS team strongly recommended that flight operations on aircraft BUNO 164176 cease and the main gearbox be removed and sent to the HTTF for installation

and continued testing in a test cell environment to provide a comparison to flight test data. Moreover, the urgency to remove the gearbox from service was a result of the HIDS team assessment that the presence of the oil dam (P/N 70351-38124-101), adjacent to the bearing was a barrier to chip migration thereby (1) preventing the chip detector from indicating the true severity of the failure development and (2) creating a reservoir of chips which may act to increase the failure progression rate. Action was taken to comply with the recommendation. Subsequent teardown and inspection confirmed that 13 of the 23 rollers in the bearing were severely spalled as shown in Figure 17. Inspection revealed a large amount of debris harbored by the oil dam, confirming the HIDS team suspicion that the oil dam acted as a chip reservoir. This is an outstanding success story, and a testament to the work being performed under this program.

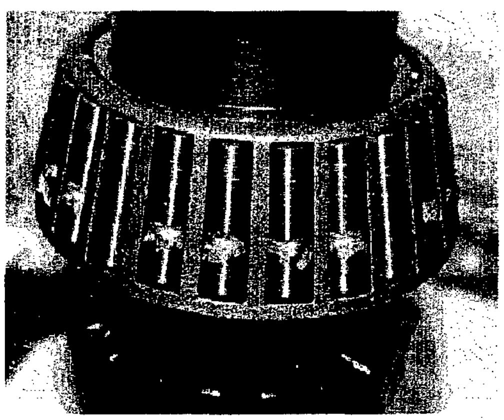

Fig. 17. SB 3313 Removed from PAX Aircraft.

Diagnostic results were categorized with respect to aircraft flight regime to define optimized system acquisition and processing requirements. A great deal of scatter was found in the value of the faulted bearing indicator. This is due to the differences in flight regime and torque. Discrete frequency excitation levels are a function of load, and a determination of what regimes produce satisfactory results is needed.

The diagnostics ability to reduce component "false removals" and trial and error maintenance practices was demonstrated. Several fleet removed components were tested and found to be fault free. Four hydraulic pumps removed for oil pressure problems were found to operate normally in the HTTF. An input module removed for chip generation was tested. No debris was generated, and the diagnostics indicated a healthy component. Subsequent teardown inspection at Sikorsky revealed no dynamic component degradation.

Methods that reduce false alarms and improve component condition assessments were demonstrated. Numerous indicators have been developed to quantify health of the drive train components. Rather than use each of these indicators in isolation, utilizing data fusion can derive additional benefit. Previous multiple sensor data fusion techniques have had great success in fault detection and classification. An automated data fusion technique currently under investigation is Hotelling's T2 Multivariate Analysis. This technique combines multiple indicators into one composite indicator. The composite indicator has been shown to increase robustness of condition calls because it changes by orders of magnitude in the presence of a fault. In addition, a reduction in false alarm calls is produced by establishing tighter control limits by taking advantage of the underlying correlation among the indicators.

In order to select the indicators that produce a more robust response, a goodness of fit test is being employed to ensure that the assumption of normality is not being violated on baseline data. All indicators not falling within the multivariate normal distribution are dropped from consideration. A correlation study is performed to further select indicators with favorable relationships. The indicators showing the strongest change in correlation between fault and baseline data are used in the T2 analysis.

The advanced statistical quality control technique has been applied to the HTTF crack propagation data and compared to current component condition call indicators. A preliminary study produced good results and will be reported under a future NAWCAD report. This technique has provided a more robust classification of the fault with a large reduction in false alarm calls. Alternative methods exist which yield a more robust estimate of the in-control parameters and this would further decrease false alarm rates while preserving the responsiveness of the T2 analysis to faults.

APPLICATION TO AGING AIRCRAFT

Diagnostics and prognostics are applicable to all phases of an aircraft's service life. As the aircraft ages, failures can be driven by multiple failure mechanisms. Experience has shown that improper maintenance, re-use of parts, rework tooling, build variability, exposure to new

operating tempos and environments, and changing mission profiles can contribute to new failure modes. In addition, aircraft are often adapted to roles for which they were not originally designed, incurring increased gross weight requirements, and operated longer than originally planned.

Model-based approaches are particularly suited to address these problems as they monitor for deviations from what is considered normal without requiring extensive data collection and training efforts. That being said, seeded fault tests jump-start the maturity of the diagnostics and prognostics by providing real-world examples of common or safety critical failure modes in a controlled and highly instrumented environment. This fault database can then be used to set limits intelligently and reduce false alarms. This approach is preferred, when feasible, to maturing a system based on field failures.

Engine degradation models such as the PPI provide information on the engine gas path state of health. During the Gulf War, military engines suffered severe erosion as a result of the fine sand characteristic of the region. The model, if employed, would have highlighted increased rates of performance degradation, and provided an increased measure of safety by triggering an alert when performance had dropped below an acceptable level. The model also enables optimization of maintenance, as trending will allow forecasting of when maintenance will be required and provides for scheduling the maintenance versus aborting the mission.

CONCLUSION

Effective diagnostics and prognostics are essential to the operation of all aircraft types, and are key to increasing safety and reliability while reducing maintenance costs. As aircraft age, new failure mechanisms are discovered. Model-based diagnostics and prognostics approaches are particularly suited to address these problems as they arise, because they do not require extensive data collection and training efforts.

REFERENCES

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[2]Hardman, W. and Frith, P., "Analysis of a Severe IGB Tooth Fault Implanted in the 8W SH-60 Drive Train Rig", NAVAIRWARCEN-ACDIVTRENTON-LR-PPE-95-7, Aug 95.